Navier-Stokes Simulation of Local Winds Over the Earth's Topography

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Abstract

A numerical approach is described that simplifies and automates the CFD solution process so that Earth scientists can utilize high-resolution Navier-Stokes flow solvers as a research tool to investigate wind events on the Earth's surface. The current approach utilizes the OVERFLOW-2 structured overset RANS code. A genetic algorithm is used to obtain an optimal multi-zone overset grid system that reduces the grid size and simulation time by maintaining high resolution over high-gradient land regions and lower resolution over low-gradient water regions. Flow simulations are presented that include flow separation and reattachment over mountainous terrain for coastal islands in Alaska (USA) and British Columbia (Canada).

1 Introduction

Earth scientists often rely on local meteorological measurements and simple linear airflow models to study how winds impact the Earth's surface. Surface winds directly impact the Earth's surface by eroding and depositing dust and soil. High speed surface winds can cause catastrophic damage to forest ecosystems throughout the world . In high latitude coastal regions of North America (southeastern Alaska) and Europe maritime cyclonic windstorms disturb forested ecosystems by snapping and uprooting trees and causing landslides. [1]

Reynolds-averaged Navier-Stokes (RANS) simulations have not been readily used to predict winds with micro-scale spatial resolution (grid resolutions under 1 Kft) because these high-resolution simulations require large computational resources, and advanced Computational Fluid Dynamic (CFD) codes often require expert knowledge to effectively use them. However, large supercomputing centers are becoming more readily available at government labs and universities. For example, NASA's Advanced Supercomputing (NAS) Division at Ames Research Center makes available to scientists 10,240 1.5 GHz Intel Itanium 2 processors. This paper describes an approach to automate much of the grid generation, flow solution, and data extraction process. The goal is to make high-fidelity RANS simulations more readily available as a

science tool for researchers with little or no CFD experience. The solution procedure is described in Section 2, numerical results are discussed in Section 3, and concluding remarks are made in Section 4.

2 Solution Procedure

The OVERFLOW-2 CFD RANS code [2] is used to simulate high-resolution viscous flow over large coastal regions of Alaska and British Columbia. This code uses overset structured grids, has a variety of steady-state and time-accurate numerical integration algorithms, and several turbulence models. A low Mach number preconditioner maintains solution accuracy and code efficiency for low-speed flow simulations. Much of the solution process has been automated in order to simplify code execution and provide a flow simulation tool for scientists that are not expert users of CFD codes.

An Automated Planetary Grid (APG) code has been developed to automatically generate overset grids and OVERFLOW-2 input files. The grid generation process begins by reading in a Digital Elevation Model (DEM) of the Earth's surface. The DEM is an ascii file that defines the terrain elevation (z) on a uniformly spaced xy-grid. The micro-scale spatial resolution is often on the order of tens to hundreds of feet. Since these coastal regions involve islands surrounded by large bodies of water, improved computational efficiency is obtained by keeping land regions at the DEM resolution and reducing the resolution of water regions by a factor of two. These water regions are flat and have small flow gradients. This is accomplished by partitioning the terrain surface into structured overset water and land zones.

The zonal partition is established by first subdividing the terrain into small water and land sub-grids, see Fig. 1. Water sub-grids are regions that only have zero (sea level) elevations, while land sub-grids are regions that have at least one non-zero elevation. The process of reassembling these sub-grids into an optimal water and land zonal topology is based on a Genetic Algorithm (GA) reported by Holst and Pulliam.[3] Certain rules and constraints are included in the optimization process. For example, grid zones obtained by reassembling sub-grids must be rectangular, a requirement of the OVERFLOW-2 code. Moreover, when forming rectangular zones, water sub-grids can be converted into higher resolution land sub-grids, but not visa versa. This is done to ensure DEM resolution is maintained over all land regions. Additional constraints include a minimum number of sub-grids in a zone, and a maximum zonal aspect ratio to reduce the GA optimization time and avoid very small isolated zones.

A two-objective GA optimization is performed, subject to the rules and constraints mentioned above, that simultaneously minimizes the total number of land zones and the total number of grid cells, including the overset zonal overlap. A "pareto front" is the result of the optimization process, see the example in Fig. 2. This pareto front represents the minimum number of grid cells for a specific number of land zones. Any other combination of land and

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water zones will have more surface cells and lie above the pareto front. In the example shown in Fig. 2, the number of land zones varies from one to five along the pareto front. Any combination of water and land zones that has more than five land zones will result in a higher number of surface cells. The choice of which combination of water and lands zones to use on the pareto front depends on the requirements of the flow simulation. For example, one may wish to have fewer land zones to simplify flow visualization or reduce the number of zonal interfaces. In the cases presented in this study, the number of zones that results in the least number of grid cells is chosen. This would correspond to five land zones in the Fig. 2 example.
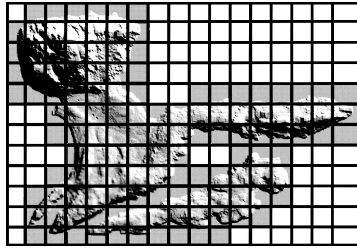
Fig. 1. Initial land (gray) and water (white) sub-grids.
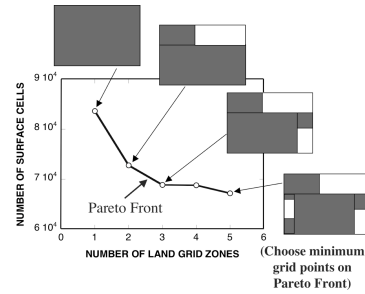
**Fig. 2.** Two-parameter GA Optimization. Land Zone (gray); water zone (white).

Once the surface zonal topology is determined, the APG code generates volume grids using a hyperbolic grid generation method. User input controls the grid attributes, e.g., initial body-normal spacing, stretching factors, and far-field grid boundary height. The APG code also automatically generates all OVERFLOW-2 input files and force/moment input files to monitor solution convergence. Post-processing software is provided to extract the flow solution at a fixed distance Above Ground Level (AGL) for data analysis and flow visualization. The web-based AeroDB framework [4] is used to run the flow solver and simplify the job submission and solution monitoring process.

3 Numerical Results

The OVERFLOW-2 RANS code [2] uses a Message-Passing Interface (MPI) for parallel processing. The Pulliam-Chaussee diagonal central-difference algorithm [5], together with matrix artificial dissipation, is used to integrate the RANS equations. Steady solutions are obtained using a multi-grid technique with local time-stepping based on a constant Courant-Friedrichs-Levy (CFL) condition. The Menter SST turbulence model [6] is used to model fully turbulent flow.

Figure 3 shows the result of the APG zoning algorithm for the Queen Charlotte Islands, British Columbia, Canada. This is an archipelago of more than 150 islands with an overall length of 170 miles and width of 83 miles. The

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surface grid resolution for land zones is 328 ft while the water zone resolution is 656 ft. Throughout this paper, the water grid resolution is always twice as coarse as land grids. The GA optimization selected 21 land grids and 15 water grids, resulting in a 25% reduction in the total grid size. Four slender water grids 8 miles wide (using exponential stretching) are added around the perimeter of the grid system to allow the turbulent boundary layer to grow to sufficient height. Typical Earth boundary layers vary from 1000 ft to over 3000 ft, depending on the time of day and local weather conditions. This 40 zone grid system consists of 262 million grid points and covers over 14,000 sq. mi. The serial (1 CPU) APG code took 30 seconds for the GA zonal optimization, and 50 minutes to generate all 40 volume grids on the NAS Columbia system.
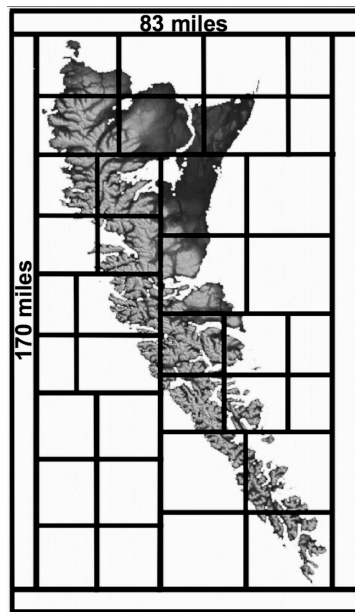
Fig. 3. GA optimized zonal grid system for Queen Charlotte Islands. Dark regions (low elevation), light regions (high elevation).
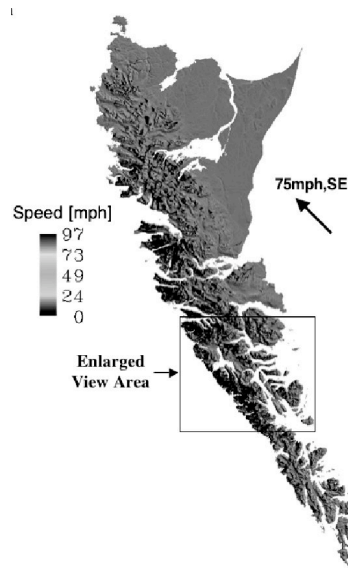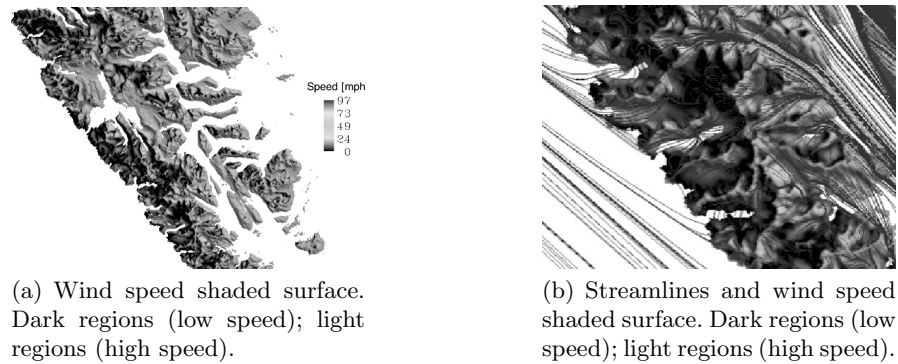
Fig. 4. OVERFLOW-2 wind speed at 32.8 ft AGL for Queen Charlotte Islands. Dark regions (low speed); light regions (high speed).
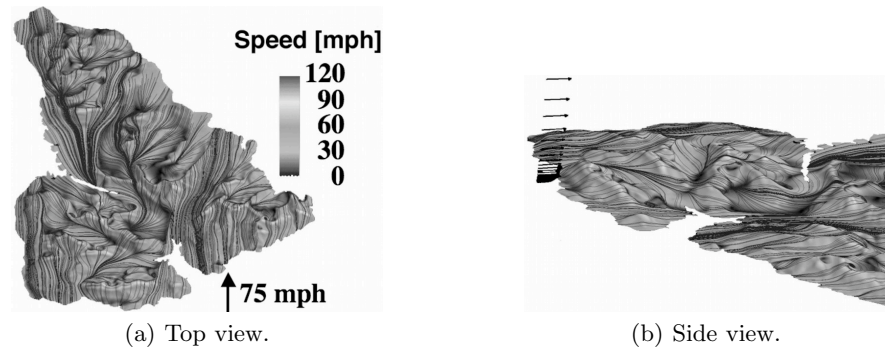
The wind speed computed by the OVERFLOW-2 RANS code is shown in Fig. 4 on a surface at 32.8 ft AGL. This high-wind event has a freestream windspeed of 75 mph from the South Easterly direction, a Reynold's Number (Re) of 700,000/ft, and a static temperature of 59 degrees Fahrenheit. The APG code automatically provides all inputs and post-processing software to utilize OVERFLOW-2's overset interpolation capability to extract the 32.8 ft AGL surface. Figure 5(a) shows an enlarged view of a portion of the

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island. Dark regions correspond to low wind speed while light regions are high wind speed. Figure 5(b) shows local streamlines constrained to the extracted surface. For the most part, the flow separates along mountain ridges and reattaches in the valleys between mountain ridges. The local wind speed also slows down as the flow traverses several mountain ridges.

Depending on the flow direction, steady solutions for this 262 million grid-point system requires 3000-5000 iterations to achieve convergence of the island's computed lift and drag coefficients, and the L_2 norm of the residual. This corresponds to 24-39 wall-clock hours using 128 CPUs on the NAS Columbia system. The data processing rate is 10^{-7} sec/iteration/grid-point.

(a) Wind speed shaded surface. Dark regions (low speed); light regions (high speed).

(b) Streamlines and wind speed shaded surface. Dark regions (low speed); light regions (high speed).

Fig. 5. Enlarged views of the Queen Charlotte Islands, 32.8 ft AGL.

(a) Top view.

(b) Side view.

Fig. 6. Wind speed shaded surface and streamlines at 27 ft AGL. Mitkof Island, Alaska. Dark regions (low speed); light regions (high speed).

Fig. 6 shows the wind speed and flow streamlines on a surface 27 ft AGL for Mitkof Island, Alaska, USA. The free stream conditions are identical to the Queen Charlotte Islands, except this high-wind event comes directly from the South. There are 4 land zones at 200 ft resolution and 3 water zones at 400 ft resolution. As before, water zones are added around the perimeter of the island to obtain an appropriate boundary-layer height. This island is approximately 20 mi long and 16 mi wide. As before, high winds and flow

separation occur near mountain ridges, and low speed reattachment occurs in the valleys. Figure 6(b) shows an enlarged side view and the approaching velocity boundary layer profile.

4 Conclusions

Automated Planetary Grid (APG) generation software has been successfully developed and demonstrated to simplify and automate the grid generation and flow solution process for the OVERFLOW-2 CFD code. This software provides an automated high-resolution RANS simulation tool for Earth scientists to investigate wind events over the Earth's topography. Examples are given where the APG software automatically generated multi-zone overset grid systems and flow-solver input files. Moreover, the APG software provides tools to automatically extract solution data on a surface at a fixed distance above ground level for scientific visualization and analysis. A robust genetic algorithm efficiently determines an optimum grid-zoning partition that reduces the total grid size and solution time by maintaining high spatial resolution over land regions (with high flow gradients) and lower spatial resolution over water regions (with lower flow gradients). The GA is flexible in that it is relatively easy to include constraints and rules that provide robust control of grid quality and zonal partition characteristics. RANS solutions using the APG software and AeroDB web-based solution framework have been presented for coastal islands in Alaska (USA) and British Columbia (Canada). The OVERFLOW-2 code is able to simulate complex separated flow over the Earth's topography.

References

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